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Degradation Factor Approach for Impacted Composite Structural Assessment
(MSFC Center Director's Discretionary Fund Final Report, Project No. 96–17)

R. Ortega, J.M. Price, and D. Fox
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February 2000

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DEGRADATION FACTOR APPROACH FOR IMPACTED COMPOSITE STRUCTURAL ASSESSMENT (MSFC Center Director's Discretionary Fund Final Report, Project No. 96–17)

1. INTRODUCTION

The use of composite laminates in aerospace structures has increased extensively over the last several years. These composites offer larger strength-to-weight ratios over metals, making them very attractive to aerospace applications. Over the years, many analysis tools have been developed to predict the behavior of the composite structures under load. However, a need remains for a tool that can predict, in a reasonable period with minimal costs, the load-carrying capacity of a composite structure that has received damage due to an impact force. Real-life examples of unintended impacts on composite structures range from a workman dropping a wrench to an in-flight impact of a bird. Currently most of the research in this area is concentrated in predicting the damage in the composite material and its subsequent damage tolerance. This approach involves several steps which include: (1) Determining the geometry of the impactor and impact force; (2) determining the damage caused by the impact including the extent of fiber breakage, delamination, and matrix cracking which involves large amounts of research in nondestructive evaluation, and impact damage progression; (3) estimating the damaged material properties to be used in the damage tolerance analysis; and (4) conducting the damage tolerance analysis and establish inspection criteria. For real-life situations, the above steps can represent long delays on a program that might not be able to afford schedule slips and cost increases.

2. OBJECTIVE

There were three main objectives of this study. First, conduct a literature search on the residual strength of impacted composites to identify promising approaches for more expedient analysis tools. Second, prepare a plan for conducting impact testing on two laminates to obtain data for the development of a strength degradation factor to be used with the undamaged elastic material properties. Third, develop a concept for assessing the structural integrity of impacted composite structures using the strength degradation factor in conjunction with available finite element analysis tools.

3. APPROACH

The basic approach was to conduct a literature search of testing methods for the impact of composite structures and the analysis tools used in assessing the residual strength of the structure. An impact test method was then chosen. This impact test method consists of dropping weights on composite panels. The three-point bend test was then chosen to test the damaged impacted panels to assess residual strength. Therefore, three-point bend specimens made of 0°/90° and quasi-isotropic AS4/3501–6 composite laminates were designed and fabricated. This material was chosen because some was left over from previous programs and was available at no cost. The only costs incurred in obtaining the specimens were the material layup and the specimen machining.

Once the test method was identified from the literature search and specimens were fabricated, a testing plan was developed. This plan included impact testing, three-point bend testing of impacted panels, and several tests on nonimpacted specimens to develop a baseline set of material properties for anchoring the results.

The next step was to develop a process for the analytical evaluation of the residual strength of an impacted composite. This included the development of finite element models of the impact process as well as the three-point bend tests. Finally, the results of the finite element models were to be correlated and compared to the three-point bend tests of the damaged and undamaged panels.

4. BACKGROUND

Over the last 30 yr, the residual strength of impacted composites has received much research attention. Several techniques for assessing the damage tolerance of impacted composites have evolved. Husman et al.[1] derived a relationship for residual strength, σ_R, in terms of the kinetic energy imparted to the specimen, W_{KE}:

$$\sigma_R = \sigma_u \sqrt{\frac{W_s - K_d \overline{W}_{KE}}{W_s}} \quad , \tag{1}$$

where $\overline{W}_{KE} = \frac{W_{KE}}{t}$, σ_u is the undamaged static strength, W_s is the work per volume required to break an undamaged specimen, t is the laminate thickness, and K_d is defined as an effective damage constant. The K_d factor relates the kinetic energy imparted to the specimen to the difference of the energy necessary to break undamaged and impacted specimens. In addition, K_d is assumed invariant to geometry and impact energy level. However, it may depend upon boundary conditions, composite material, and layup. Two experimental tests are required to express the residual strength in terms of the imparted kinetic energy. The two tests are one tension test on an undamaged specimen and one tension test on an impacted specimen without through penetration. Husman's work showed experimental data that agree well with equation (1) for in-plane tension loads of 0°/90° laminates.

The ratio σ_R/σ_u is equal to the ratio of modulii, E_d/E, of the damaged and undamaged tension specimens for pure 0° laminates by following a procedure described by Mallick.[2] Furthermore, σ_R/σ_u and E_d/E is equal to the ratio of load-carrying, cross-sectional area of the damaged and undamaged tension specimens, A_d/A. These relationships do not hold true for laminates of varying orientations. Nevertheless, more involved expressions can be obtained for multidirectional laminates relating the ultimate strength ratio to the modulii of the damaged and undamaged tension specimens. As an example, an expression relating the ultimate strengths and modulii of damaged and undamaged 0°/90° laminates can be derived as

$$\frac{\sigma_R}{\sigma_u} = \frac{\left(\frac{K_0 A_0 E_L + K_{90} A_{90} E_T}{K_0 A_0 + K_{90} A_{90}}\right)\varepsilon_{tu} + \frac{K_0 A_0 E_L}{K_0 A_0 + K_{90} A_{90}}\left(\varepsilon_{lu} - \varepsilon_{tu}\right)}{\left(\frac{A_0 E_L + A_{90} E_T}{A}\right)\varepsilon_{tu} + \frac{A_0 E_L}{A}\left(\varepsilon_{lu} - \varepsilon_{tu}\right)} \quad , \tag{2}$$

where

E_L = longitudinal (0°) ply modulus
A_0 = undamaged load-carrying, cross-sectional area of 0° plies
K_0 = ratio of the damaged to undamaged load-carrying, cross-sectional area of 0° plies

E_T = transverse (90°) ply modulus
A_{90}= undamaged load-carrying ,cross-sectional area of 90° plies
K_{90}= ratio of the damaged-to-undamaged load carrying, cross sectional area of 90° plies
A = total specimen load-carrying, cross-sectional area (A_0+A_{90})
ε_{lu} = longitudinal (0°) ply failure strain
ε_{tu} = transverse (90°) ply failure strain.

A relationship between K_d, K_0, and K_{90} can be obtained by combining equations (1) and (2). Therefore, for the 0°/90° laminate, an expression relating the kinetic energy imparted in the specimen during impact and the fraction of damage caused by the impact process can be obtained by conducting tensile tests of damaged and undamaged specimens. However, equation (2) only applies to the 0°/90° laminate under uniaxial tensile loading. Different and more complicated expressions are required for varying layups. Also, the expression is not valid for bending or multiaxial loads under varying levels of specimen constraint. In addition, K_0 and K_{90} cannot be resolved without additional information from the impact event or through the use of nondestructive techniques. One can conclude that the usefulness of developing expressions such as equation (2) for individual cases is limited or nonexistent except to point out that there is a direct relationship between the kinetic energy imparted during impact, the damage caused, and the residual strength of laminated composites.

The impact damage can be evaluated by the use of nondestructive techniques such as ultrasonic, acoustic emission, and, x-radiography techniques as discussed by Agarwal and Broutman.[3] However, the use of nondestructive techniques requires a great deal of effort and is not always feasible on a given piece of hardware. Another possible way of evaluating the damage caused by impact is to model the event using finite element modeling. Sun[4] used finite element models to estimate the amount of energy that causes damage in the area of impact. Hackett[5] used finite element modeling to simulate the process by which the internal damage propagates. This was accomplished by modeling the individual constituents of the composite and including the effects of matrix creeping, and the statistical nature of the fiber strength, fiber spacing, and manufacturing flaw distributions. Choi and Chang[6–8] developed finite element programs to estimate the impact damage zone including ply delamination and matrix cracking.

Whereas Husman et al.[1] used an empirical relationship relating residual strength to the kinetic energy imparted to the specimen, Kutlu[9] and Shahid[10] predicted failure by using damage accumulation criteria for matrix cracking, fiber-matrix shearing failure, fiber breakage for tensile loads, and buckling instability criteria for compression loads. The initial damage was modeled by representing the reduced effective stiffness as a function of matrix-crack density for matrix cracking and fiber-matrix shearing failure, and fiber failure area and fiber interaction length for fiber-breakage failure. In addition, ply transverse tensile strength and shear strength are calculated as functions of crack density in the individual plies. Damage progression is accomplished by continually recalculating the effective stiffness and effective strengths as the plies meet the required damage level for a mode of ply failure. The final failure load is predicted once the laminate can no longer sustain additional loads.

5. SPECIMEN DEFINITION AND FABRICATION

AS4/3501–6 composite material was selected for specimen fabrication. The material was obtained from another program and was supplied at no cost. Two specimen layups were chosen for this project. Eighty 9.75×3 in. specimens were fabricated for each layup. The layups are as follows:

Panel 1: 16-ply–[0, 45, 90, –45, 0, 45, 90, –45] symmetric (quasi-isotropic composite)
Panel 2: 16-ply–[0, 90, 0, 90, 0, 90, 0, 90] symmetric (0°/90° composite).

Each panel, measuring approximately 48×49 in., was laid up and vacuum cured to a matted finish. Each specimen was then milled from these panels. A total of 160 specimens, 80 from each panel, are available for testing.

6. TESTING SETUP DEFINITION

A drop weight apparatus is envisioned for the impact tests of the specimens. This method is preferred because of its simplicity and there is no kinetic energy loss on the impactor due to guide rail friction. However, the rebound velocity of the impactor and the maximum rebound height are difficult to determine. This makes it more difficult to establish the transfer of energy onto the specimen. The basic test setup is shown in figure 1.

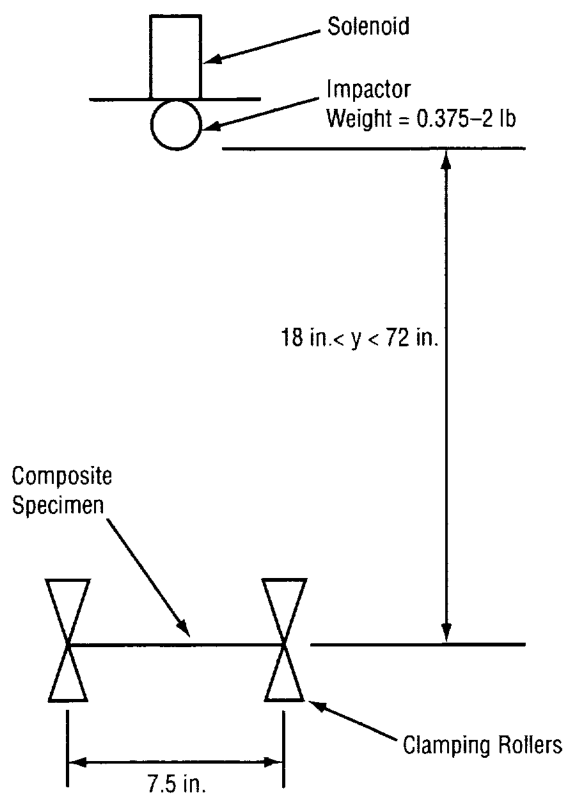

Figure 1. Impact test setup.

Four stainless steel 316 ball sizes (1.375, 1.75, 2, and 2.5 in.) were chosen for the impact tests. These sizes were chosen based on the kinetic energy available at impact as compared to the kinetic energy at impact of the tests conducted by Husman et al.[1] Given the differences of test setup, the proposed impactor sizes for this project are much larger than those used by Husman et al.[1] However, the chosen sizes seem reasonable for real-life examples of the handling of composite structures. The height variation from 18–72 in. allows variation of kinetic energy for each given ball size, thus, allowing some assessment of impactor-size variation. It is proposed that four heights be chosen and tested with four specimens for each ball size. This gives 64 impact specimens for each composite layup. The 16 remaining samples will be used for the nonimpacted bend tests and serve as spares.

Impacted and nonimpacted specimens are to be tested in a three-point bend apparatus. The 3-in.-wide specimens with an unsupported span of 7.5 in. will be tested on an MTS® Systems Corporation tensile testing machine with a 5,000-lb load capacity. The tension side (bottom) of the specimen will be tested with a strain gauge when appropriate. Stroke displacement, load, and strain will be recorded. The test setup is shown in figure 2.

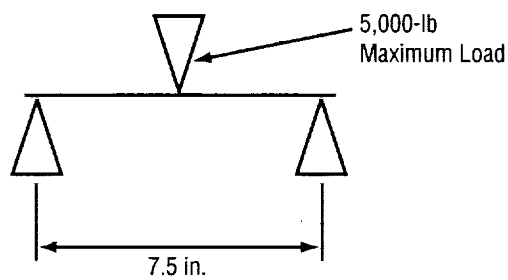

Figure 2. Bend test setup.

7. MODEL DEVELOPMENT

A parametric defined finite element model of a steel ball impacting the 0°/90° composite was developed. The three-dimensional finite element model is composed of the finite element program ANSYS® 5.3,[11] layered structural shell elements modeling the AS4/3501–6 composite plate, three-dimensional 10-node tetrahedral structural solids for the steel ball impactor, and three-dimensional point-to-surface contact elements. The input parametric variables include the steel ball diameter, ply thickness, support span width for the plate, width of the plate, and drop height. The composite plate has pinned boundary conditions at the span supports. The contact elements attach to the steel ball and the composite plate to keep track between the two parts until contact is established. When contact is achieved, the load is transferred from one part to the other. ANSYS uses a normal contact stiffness value used to determine contact forces. The value of normal contact stiffness is a user-assigned value. The value needs to be as high as possible to ensure contact without the parts going through one another. However, arriving at this value is an iterative, time-consuming process. A sample case for the model is shown in figure 3. In this sample case, the steel ball diameter is 2.25 in. and the drop height is 72 in. The input deck for this model is enclosed in the appendix. The quasi-isotropic composite case can be obtained by modifying the real card section of the input deck.

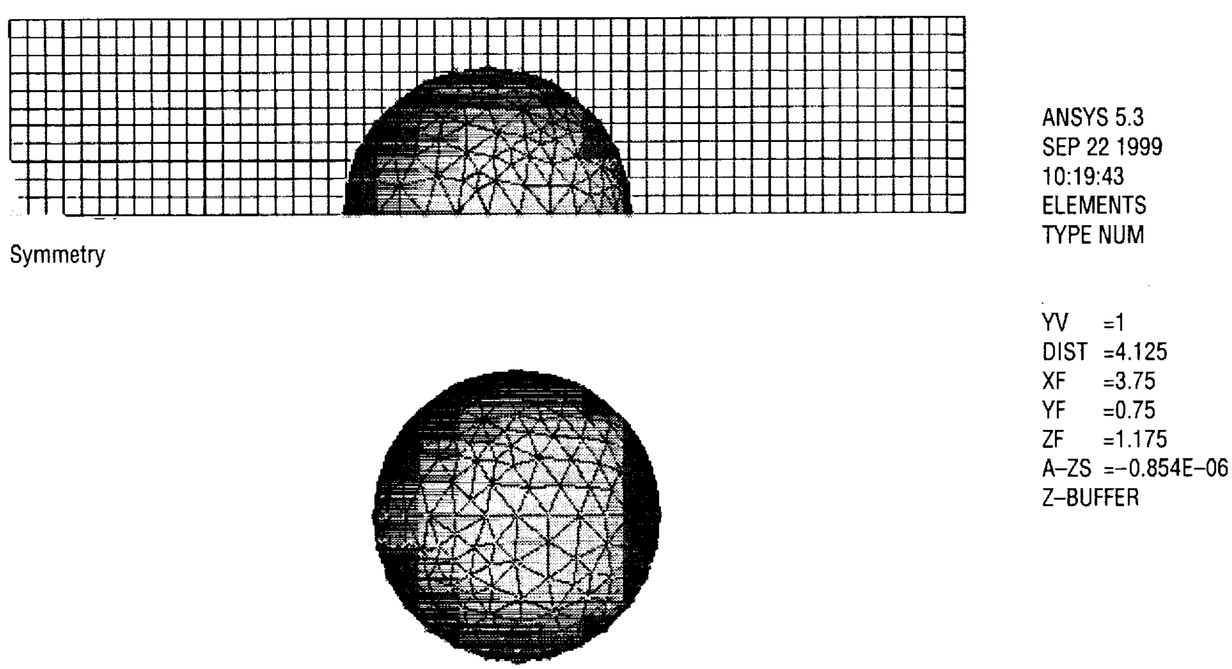

Figure 3. Impact model mesh.

The material properties used in this model are shown in table 1. The composite properties were obtained from Tsai[12] and the *DOD/NASA Advanced Composites Design Guide.*[13] It was assumed that Ez=Ey, nuxz=nuxy=nuyz, and Gxy=Gxz. Additional research or material characterization is needed to determine the adequacy of the properties listed.

Table 1. Material property data.

Property	AS4/3501–6	Stainless Steel
Modulus, Ex (psi)	2.07E+07	3.00E+07
Modulus, Ey (psi)	2.00E+06	3.00E+07
Modulus, Ez (psi)	2.00E+06	3.00E+07
Poisson's Ratio, nuxy	0.3 (prxy)	0.33
Poisson's Ratio, nuxz	0.3 (prxz)	0.33
Poisson's Ratio, nuyz	0.3 (pryz)	0.33
Shear Modulus, Gxy (psi)	1.03E+06	–
Shear Modulus, Gxz (psi)	1.03E+06	–
Shear Modulus, Gyz (psi)	7.69E+05	–
Density (lb sec^2/in.)	1.47E–04	7.61E–04

A composite failure criterion needs to be incorporated in the model to determine the failed layers and area of the composite. ANSYS has three built-in failure criteria that can be used. These are the maximum strain failure criterion, the maximum stress failure criterion, and the Tsai-Wu failure criterion. A fourth criterion based on the maximum shear stress criterion can also be included as a user-defined input. This fourth criterion is highly recommended in a paper by Hart-Smith.[14]

Finally, the bend test model will be obtained by taking the composite panel section of the impact model mesh and applying a load to the nodes at midspan. Both, the impacted and nonimpacted specimens are to be modeled. The area of damage will be modeled by modifying the properties of those elements to eliminate the composite layers that have been damaged. Failure in the model will be an iterative process of increasing the load until a limit maximum load is reached.

8. SAMPLE CASE MODEL RESULTS

The displacement results of the sample case are shown in figure 4.

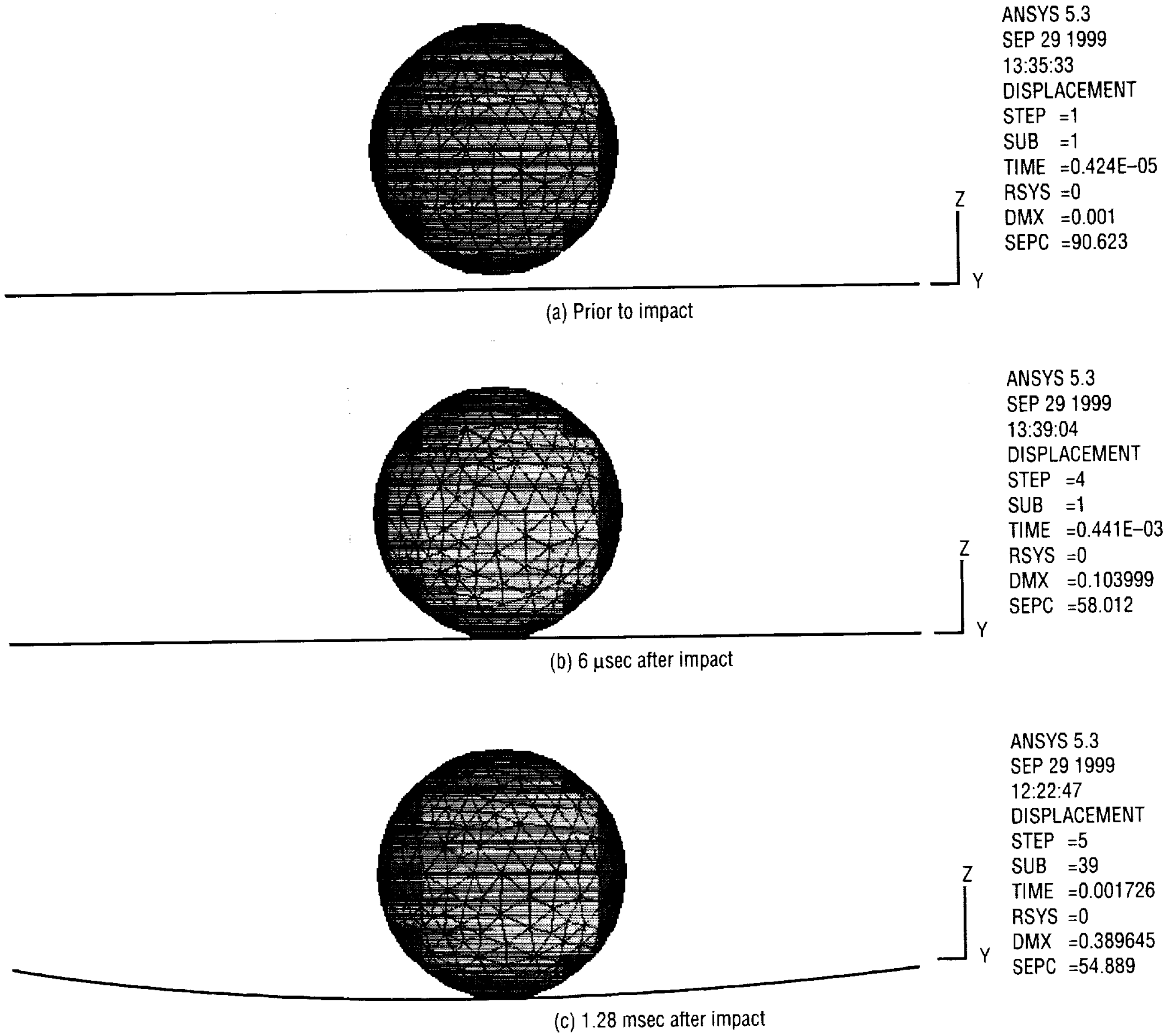

Figure 4. Composite model impact displacement results.

The stress results have shown considerable oscillation over the period observed thus far. Additional effort is needed in understanding the reason for the oscillation and in making appropriate changes as necessary. Some of this additional effort should include variations in mesh size at the immediate contact area and increasing the observation period. The time-dependent principle stresses are shown in figure 5.

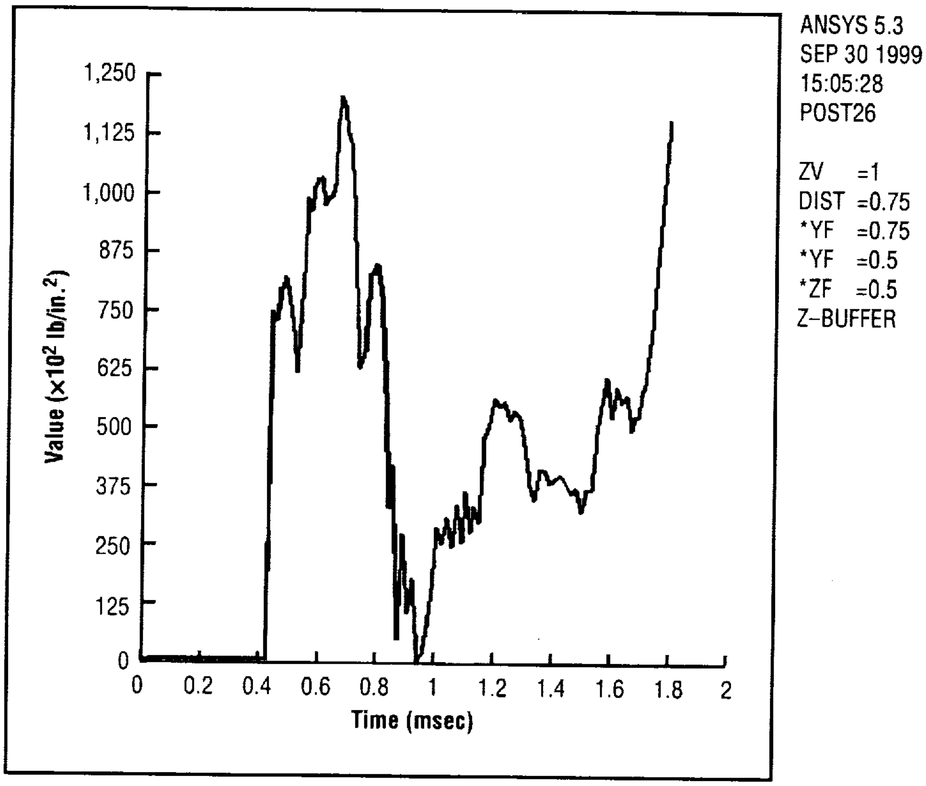

Figure 5. Maximum principle stress versus time results at the center of the panel.

9. IMPACTED COMPOSITE STRUCTURAL ASSESSMENT APPROACH

Although the work has not been completed, the envisioned process of assessing the structural integrity of impacted composite structures is as follows:

1. For the given layup, build a finite element model of the composite structure. Run a load case of a structural test (such as a proof test) that has been carried out on the structure where data are available. This step is necessary to anchor the model's elastic properties, geometry, and boundary conditions.

2. Determine the impact object geometry, mass, speed, acceleration, and location of impact.

3. Model the impact process to determine the damage zone. Due to computational limitations, a submodel of the structure might be needed for the given structure. Determine the degradation of the individual plies in the damage zone. Anchor to any available impact data.

4. Run the model under operating loads with degraded properties for the plies and location that sustained damage.

5. Determine whether failure occurs.

In this study, the composite plate represents the composite structure. The bend test of the undamaged panel is to be modeled to check properties and boundary conditions. The impact test and subsequent three-point bend tests will generate the data to verify the procedure of first determining the damage zone, and then predicting failure under load.

10. CONCLUSIONS

A finite element approach for assessing the integrity of impacted composite structures using a material degradation factor was documented. The work effort to successfully complete this program was initially estimated to be 33 man-months. Of the requested 33 man-months, only 4–5 man-months were actually spent working on this project over a span of 4 yr. During this time, a literature search was conducted, composite specimens were designed and procured, a finite element model of the impact process was built, and the required reports for the program were submitted as necessary. However, much work is needed to complete the goals of the program. The requested amount of work could not be accomplished because of responsibilities to other programs with higher priority. Given the current workload, it is impractical to continue this program at this time. Perhaps, the intent of this effort can be renewed in future Center Director's Discretionary Fund proposals.

APPENDIX—LISTING OF IMPACT FINITE ELEMENT MODEL

The following are the line commands for the finite element model in ANSYS, release 5.3:

```
/filename,composite
/prep7
spdiam=2.25
sprad=spdiam/2
plythk=.00625
span=7.5
width=3
vel=30
et,1,99
keyopt,1,2,0
keyopt,1,3,0
keyopt,1,4,0
keyopt,1,5,1
keyopt,1,6,1
keyopt,1,8,1
r,1,16,0
rmore,,,,,,
rmore,1,0,plythk,1,90,plythk
rmore,1,0,plythk,1,90,plythk
rmore,1,0,plythk,1,90,plythk
rmore,1,0,plythk,1,90,plythk
rmore,1,0,plythk,1,90,plythk
rmore,1,0,plythk,1,90,plythk
rmore,1,90,plythk,1,0,plythk
rmore,1,90,plythk,1,0,plythk
rmore,1,90,plythk,1,0,plythk
rmore,1,90,plythk,1,0,plythk
rmore,1,90,plythk,1,0,plythk
rmore,1,90,plythk,1,0,plythk
mp,ex,1,20.7e6
mp,ey,1,2e6
mp,ez,1,2e6
mp,prxy,1,.3
mp,prxz,1,.3
mp,pryz,1,.3
mp,gxy,1,1.03e6
```

```
mp,gxz,1,1.03e6
mp,gyz,1,.769e6
mp,dens,1,1.474e-4
et,2,92
mp,ex,2,30e6
mp,nuxy,2,.33
mp,dens,2,7.61e-4
et,3,49
keyopt,3,7,1
r,3,60e3,,,,1
et,4,49
keyopt,4,7,1
r,4,60e3,,,,1
real,1
type,1
mat,1
rectng,0,span,0,width/2
esize,sprad/8
amesh,1
nsel,s,loc,x,0
d,all,ux,0,,,,uy,uz
nsel,a,loc,x,span
d,all,uz,0
lsel,s,loc,y,0
dl,all,1,symm
local,12,0,span/2,0,sprad+.1,,,90
wpcsys,1,12
sphere,sprad,,0,180
wpcsys,1,0
csys,0
eshape,1,2
esize,sprad/4
type,2
mat,2
real,2
vmesh,1
type,3
mat,3
real,3
local,13,2,span/2,0,.1+sprad
nsel,s,loc,x,sprad-1e-4,sprad+1e-4
csys,0
nsel,r,loc,z,.099,.1001+sprad
cm,sphereo,node
```

```
nsel,s,loc,x,span/2-sprad,span/2+sprad
nsel,r,loc,y,-.0001,1.1*sprad
nsel,r,loc,z,-.05,.05
cm,shello,node
cmsel,s,sphereo
*get,numb,node,0,count
*do,in,1,numb,1
*get,nv,node,0,num,min
*get,xv,node,nv,loc,x
*get,yv,node,nv,loc,y
nsel,u,node,,nv
cm,dummy,node
nsel,s,node,,nv
cm,contact,node
cmsel,s,shello
nt=node(xv,yv,0)
*get,xxv,node,nt,loc,x
*get,yyv,node,nt,loc,y
nsel,r,loc,x,xxv
nsel,r,loc,y,yyv
nsel,r,loc,z,0
esln
esel,u,type,,3
nsle
cm,target,node
cmsel,a,contact
gcgen,contact,target
cmsel,s,dummy
*enddo
C***End loop 1
type,4
mat,4
real,4
cmsel,s,shello,node
*get,numb,node,0,count
*do,in,1,numb,1
*get,nv,node,0,num,min
*get,xv,node,nv,loc,x
*get,yv,node,nv,loc,y
nsel,u,node,,nv
cm,dummy,node
nsel,s,node,,nv
cm,contact,node
```

```
cmsel,s,sphereo
xf=xv-span/2
*if,xf*xf+yv*yv,gt,sprad*sprad,then
cmsel,s,dummy
*cycle
*endif
fr=.1+sprad-sqrt(sprad*sprad-yv*yv-xf*xf)
nt=node(xv,yv,fr)
nsel,s,node,,nt
esln
esel,u,type,,3
nsle
csys,13
nsel,r,loc,x,sprad-1e-4,sprad+1e-4
csys,0
cm,target,node
cmsel,a,contact
gcgen,contact,target
cmsel,s,dummy
*enddo
C***End Loop 2
allsel
nsel,s,loc,z,.05,20
nsel,r,loc,y,0
d,all,uy,0,,,,rotx,rotz
allsel
sbctran
r,3,50e6,,,,1
r,4,50e6,,,,1
save
fini
/solu
antype,transient
ti=0
outress,all,all
autots,on
timint,off
nsel,s,loc,z,.05,10*sprad
d,all,uz,-.001
nsel,r,loc,x,.4987*span,.50133*span
d,all,ux,0
ti=.001/velo
time,ti
```

```
nall
nsubs,1,1,1,on
acel,,,0
solve
yes
timint,on
nsel,s,loc,z,.05,10*sprad
ddel,all,uz
nall
eall
td=(sqrt(velo*velo+2*az*.1)-velo)/az
ti=ti+.00001*.99*td
time,ti
acel,,,az
nsubst,1,1,1,on
solve
yes
ti=ti+.99*td
time,ti
nsubst,10,10,1,on
solve
yes
ti=ti+1.6*td
time,ti
nsubst,60,60,40,on
/nerr,40,600000
solve
yes
/solu
antype,transient,rest
ti=ti+1.6*td
time,ti
nsubst,60,60,40,on
/nerr,40,600000
solve
yes
fini
```

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13. ABSTRACT *(Maximum 200 words)*

This technical memorandum documents the results of the research to develop a concept for assessing the structural integrity of impacted composite structures using the strength degradation factor in conjunction with available finite element tools. For this purpose, a literature search was conducted, a plan for conducting impact testing on two laminates was developed, and a finite element model of the impact process was created. Specimens for the impact testing were fabricated to support the impact testing plan.

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